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Description of Three Candidate Cassini Satellite Tours

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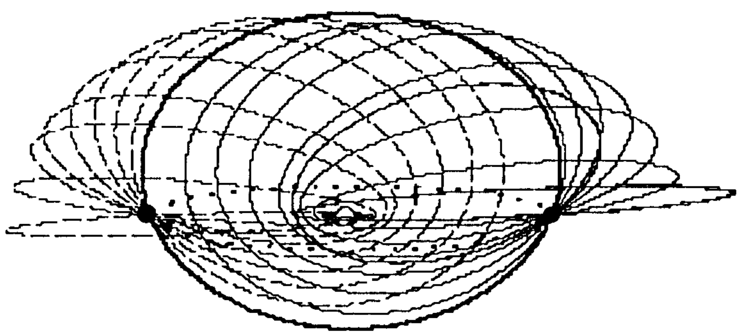

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Description of Three Candidate Cassini Satellite Tours

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In July of 2004, Cassini will become the first spacecraft to insert into orbit about Saturn. During the 4 year tour, the spacecraft trajectory is modified by gravity assists provided by the Saturnian satellites. This paper describes three candidate Cassini satellite tours which are indicative of tours currently under consideration. The first 1.2 years of the tour has been finalized; however, the remaining 2.8 years will not be selected until the year 2000 time frame. A comparison of these three tours illustrates the tradeoffs involved in the design process and provides a preview of the characteristics of the final tour.

INTRODUCTION

The successful launch of the Cassini spacecraft on October 15, 1997 has set the stage for a spectacular investigation of the Saturnian system. After a 6.7 year interplanetary cruise, the combined orbiter/Huygens Probe will insert into orbit about Saturn on July 1, 2004. The Huygens Titan Probe will descend through the atmosphere of Titan at the first Titan encounter. The orbiter will conduct a 4 year tour of Saturn, its rings, satellites, and magnetosphere.

A satellite tour is a spacecraft trajectory which is modified by gravity assists obtained from one or more of the planet's natural satellites. Since Titan is the only Saturnian satellite massive enough to provide significant gravity assist, the orbiter trajectory is shaped by more than three dozen Titan flybys during the 4 year tour. The exact number of Titan flybys is tour dependent. Flybys of the other icy satellites of Saturn must be obtained on orbits already targeted to return to Titan to minimize propellant consumption.

Since the satellite tour determines the science observation geometry, extensive interaction between the mission design team and the Cassini Project Science Group (PSG) is required. Interaction with navigation and ground systems teams is also crucial. Iteration between the PSG and tour designers during the last several years has narrowed the types of satellite tours under consideration to two classes of tours. Three candidate tours from these two classes are described in this paper.

The first 1.2 years of all the tours presented are identical and will be part of the final tour. The first 1.2 years of the tour accomplished many key science objectives and was accepted by all Project teams[1]. Significant progress has been made in the design of the remaining three years, but final tour selection will not occur until after the Earth flyby in August 1999.

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The key decisions which will lead to a final tour selection concern the tradeoff between science return and mission operability. Since Titan gravity assists are used to modify the trajectory and Titan is of itself of great scientific interest, tours with large numbers of Titan flybys tend to be favored by science teams. However, large numbers of Titan flybys reduce the time between flybys which places great stress on the ground system and may introduce significant risk of failing to complete a specified tour. The current tours are much more stressful to the ground system than those envisioned five years ago and further analysis of these considerations will have a major impact on the final tour design.

Since most of the orbital mechanics employed in the tours described in this paper have been discussed extensively by previous literature[2,3,4], emphasis will be placed on describing tour design techniques new to Cassini. Many of the tour design techniques have been inherited from design of the highly successful Galileo tour which has already completed its primary mission.

Gravity Assist Technique

The spacecraft must always return to Titan since only Titan is massive enough to provide the gravity assist required to change the spacecraft orbit. Titan is more than 52 times more massive than the next largest Saturn moon. A spacecraft maneuver can also change the trajectory, but insufficient ΔV is available to do much more than ensure desired flyby conditions. A close Titan flyby can change the direction of the velocity of the spacecraft with respect to Titan, referred to as the V_∞, but not its magnitude. By changing the direction of the Titan relative spacecraft velocity, the direction and magnitude of the spacecraft velocity relative to Saturn can be changed. The lower the flyby altitude, the more the V_∞ direction can be changed and the greater the Saturn centered orbit may be modified. The minimum Titan flyby altitude is 950 km and is dictated by the density of Titan's atmosphere and its affect on the spacecraft's ability to maintain attitude. A single Titan flyby at 950 km provides a gravity assist ΔV of 840 m/s which alone is greater than the entire tour ΔV allocation.

Tour Design Process

The design process leading to the types of tours described in this paper is briefly described. Since Titan is the only Saturnian satellite massive enough to provide sufficient gravity assist, initial tours composed of only Titan flybys were constructed and evaluated by science teams. Such "Titan-only" tours were limited to 3.5 years duration to reserve 6 months for inclusion of about 6 close icy satellite flybys as well as meet other constraints such as restrictions on flyby and maneuver times. These Titan-only tours were quickly designed using the STOCK[5] program in an Excel spreadsheet environment . These tours demonstrate most of the basic science observation geometry of a complete 4 year tour with the significant exception of demonstrating the number and quality of targeted icy satellite flybys. Analysis gave the tour designers confidence that given 6 months, a desirable set of icy satellite flybys could be incorporated[6]. This approach was not possible for the Galileo tour design, since for Galileo tours, 4 massive moons were utilized for gravity assist instead of a single moon.

Satellite tours were grouped into classes based on the time history of the spacecraft orbit inclination and orientation. Orbit orientation is the location of the spacecraft orbit with respect to the Sun and is usually expressed by the local solar time of spacecraft orbit apoapsis (Figure 1). For example, the spacecraft orbit is in the dawn orientation when the spacecraft apoapsis lies over the dawn terminator of Saturn. The inclination/orientation profile is the foundation of any Saturn centered satellite tour since it dictates how satellite gravity assists will be used to shape the spacecraft trajectory.

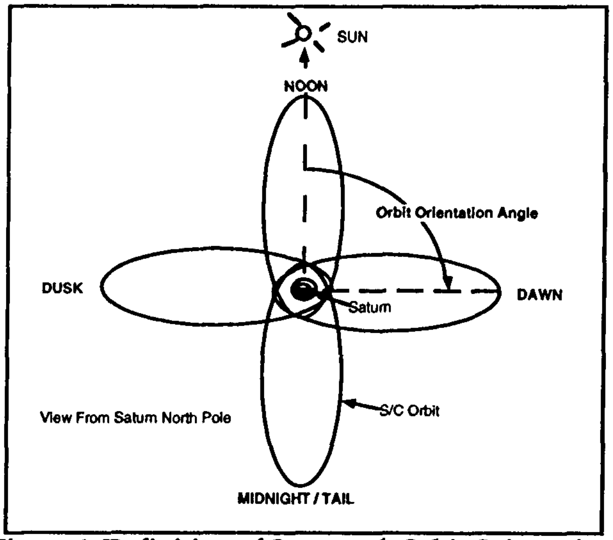


Figure 1 Definition of Spacecraft Orbit Orientation

After 18 classes of Titan-only tours were evaluated by the PSG, two classes were selected for detailed study, i.e., incorporation of targeted icy satellite flybys and compliance with all other tour constraints. The two tour classes are referred to as "T9" and "T18". The class numbers have no real significance - they merely refer to the 9th and 18th tour class. In this paper a single T9 tour and two T18 tours are described.

The STOUR[7] program was used to design tours which included icy satellite flybys. The orbits are modeled by simple two-body conics, and ballistic icy satellite flyby opportunities were identified using the VTOUR[8, 6] program. VTOUR identifies ballistic icy satellite flyby opportunities once the Titan-to-Titan transfer orbit is specified. Flyby aimpoints were optimized to minimize ΔV using the CATO[9] program. CATO models the trajectory with high precision numerical integration and uses the STOUR conic orbits as initial estimates. Unlike the development of Titan-only tours, creating a complete integrated tour is very time consuming and requires many weeks or months to create a single tour.

Creating a complete T9 class tours is quite challenging since only 4.6 months were available in the Titan-only tour for incorporation of icy satellites and other ground system constraints. To date, only one T9 class tour, referred to as T9-1, has been completed and is described in this paper. The T18 tour class has more time available for incorporation of icy satellites than the T9 class. Therefore, 5 complete T18 class tours have been completed and are referred to as T18-1 to T18-5. Two tours, referred to as T18-4 and T18-5, which illustrate the extremes in terms of science return and mission operability in the T18 class are presented in this paper. In general, the T9 class tour is considered to be the ultimate science tour but repeatedly violates some ground system constraints, whereas the T18 class tours represent a more balanced approach between science return and mission operability. The advantages and disadvantages of each tour class and the tours within them will be addressed in this paper.

Constraints

Doppler tracking data is degraded below Sun-Earth-Probe (SEP) angles of 5° due to solar interference and is unusable below ~3°. No maneuvers associated with flybys are permitted at times when SEP is below 3° [10]. Additional time periods on either side of the conjunction limit are also reserved for post-flyby cleanup and pre-flyby navigational maneuvers. The end result is that for a span of 18.3 d centered about superior conjunction, no targeted flybys are permitted. For the Cassini tour, superior conjunction occurs on 1) July 8, 2004, 2) July 23, 2005, 3) August 7, 2006, and 4) August 22, 2008.

The minimum time interval between any two targeted satellite flybys is constrained to be 16 d in order to reserve time for tracking and incorporation of pre- and post-flyby statistical maneuvers. Additionally, the number of consecutive 16 d intervals is limited to 4 in order to reduce operations stress[10]. After four 16 d intervals occur, the ground system requires an interval of 48d between flybys, or alternately 2 intervals of ~32 d each, to act as a break. This constraint may be violated once per tour. The ground system also requires that no maneuvers, flybys, or occultations occur during a 9 day period starting the Saturday morning before the Christmas holiday until the end of day on the following Sunday. One violation per tour of this constraint is also permitted.

During the design phase in which these tours were created, the total tour ΔV was required to below that available at a 75% confidence level. After the recent launch, the Project has raised the required ΔV confidence level to 95% which effectively removes most previous tour designs from consideration.

INITIAL ORBIT

The first Saturn orbit is the largest period orbit of the tour and contains many mission critical maneuvers and events. The Huygens Probe is separated from the Orbiter and delivered at the first Titan flyby which occurs near the end of the initial orbit. The initial orbit design for all tours in the T9 and T18 tour classes, as well as any future tours, has been completed and will be part of any future tour[1].

Tour Start Date

All tours start at Saturn orbit insertion (SOI) which occurs on July 1, 2004. The insertion date was chosen to enable a targeted flyby of the Saturn's most distant icy satellite Phoebe 19 days before SOI. This will be the only opportunity for a close Phoebe flyby during the tour since Phoebe's orbital distance is ~215 Saturn radii (1 Rs=60,330 km) which is beyond the reach of all orbits in the tour. The closest approach distance to Phoebe is 55,990 km which is near the minimum distance possible without expending ΔV due to the inclination of Phoebe's orbit and the declination of the interplanetary trajectory. Reducing the closest approach distance would require significant ΔV in the critical time period just before SOI and was therefore not considered. Phoebe still nearly fills the narrow angle camera field of view and imaging resolution ~60 times better than obtained by Voyager will be available. The solar phase angle varies from about 61° to 75° during the flyby.

Initial Orbit Events

The spacecraft approaches Saturn from below the ring plane, passes through the F-G gap in the ring plane at 2.627 Rs (158,500 km), and then begins the orbit insertion burn about 15 minutes later. The main engine burn of ~95 minutes provides a ΔV of 622 m/s (including gravity losses) and is biased such that it ends at Saturn closest approach. The biased burn permits remote sensing of the ring plane during the time period from Saturn closest approach to the next ring plane crossing about 2 h later but results in a ΔV penalty of about 44 m/s. The closest approach distance to Saturn is about 1.3 Rs and brings the spacecraft closer to Saturn and the inner rings than at any other time during the tour.

The SOI maneuver places the spacecraft in a highly elliptical initial orbit with a periapsis radius of 1.3 Rs, a period of ~148 days, and an inclination of ~17° (Figure 2). About 86 days after SOI, a large deterministic maneuver, referred to as the periapsis raise maneuver, raises periapsis beyond the ring plane to 8 Rs to avoid future passes through potentially hazardous portions of the ring plane and also sets up the required geometry to deliver the Huygens Probe at the first Titan flyby. The maneuver requires a ΔV of 335 m/s and is placed ~13 days after apoapsis to minimize total ΔV.

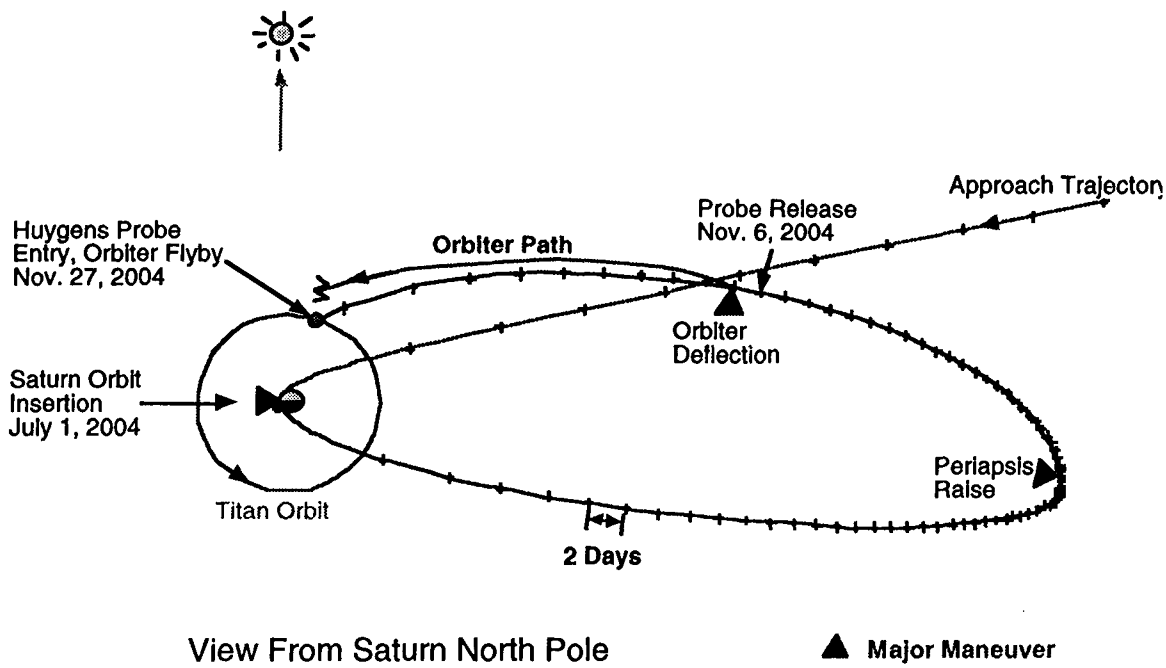


Figure 2 Initial Orbit Geometry

Huygens Probe Delivery

The Huygens Probe is delivered near the end of the initial orbit at the first Titan flyby (Figure 2) and has a significant impact on the orbiter satellite tour. The Huygens Probe carries a suite of 6 instruments and will descend on parachute through the dense Titan atmosphere for up to 2.5 hours and then touchdown on the surface where it will continue to take measurements should it survive landing[10]. The delivery of the Probe establishes the Titan relative V_∞ of the orbiter during the tour, the epoch of the first Titan flyby which impacts the availability of future icy satellite flybys, and constrains the Titan gravity assist options at the first two Titan flybys. The option to deliver the Probe at the second Titan flyby must also be preserved as a contingency option.

About 40 days after the periapsis raise maneuver, the combined orbiter/Probe spacecraft is targeted to the final Probe aimpoint. The Probe is targeted to achieve a V_∞ of 5.75 km/s, B-plane angle of -60° (with respect to the Titan equator), and flight path angle of -64° at an altitude of 1270 km[10]. The Probe descends in the sunlit portion of Titan's northern hemisphere resulting in a final touchdown at ~18° N. latitude and ~209 E. longitude. Design of the Probe trajectory up to the interface altitude of 1270 km is the responsibility of JPL - after this point, the European Space Agency (ESA) is responsible for all Probe trajectory design.

The Probe separates from the Orbiter 21.1 d before Probe entry into the Titan atmosphere on November 27, 2004 (Figure 2). An orbiter deflection maneuver (ODM) of 49 m/s is performed 2 days later to shift the orbiter aimpoint from the Titan impacting trajectory to the desired orbiter flyby aimpoint. Note that the depiction of the post-ODM orbiter trajectory in Figure 2 is exaggerated. The ODM maneuver also delays the orbiter's closest approach to Titan by 4 hours providing a clear and relatively stable view of the Probe so that it can record the entire Probe descent of ~2.5 h for later playback to the ground (Figure 3). The orbiter aimpoint is selected to reduce orbit period and insure satisfactory orbiter to Probe relay link margins. The orbiter B-plane angle at both the first and second Titan flybys is constrained to be between -24° and -75° and altitude is constrained at 1200 km in order to insure acceptable radio relay link margin[10]. The ODM ΔV reduces the orbiter V_∞ at the first Titan flyby to ~5.54 km/s. Due to these constraints, the orbiter Titan closest approach time can not be altered by more than a few minutes without incurring significant ΔV penalty.

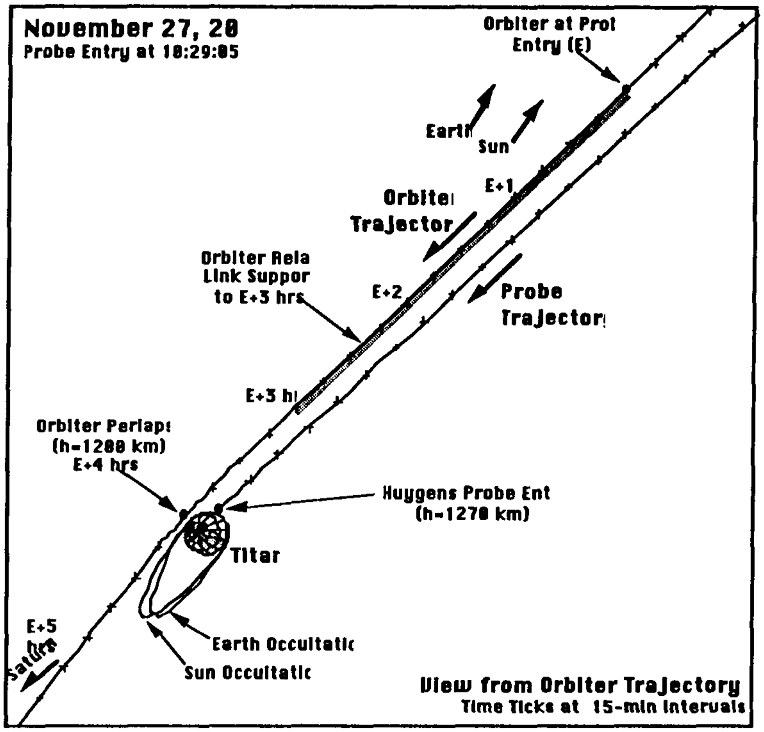


Figure 3 Orbiter and Probe Trajectories Near Probe Entry

REQUIRED TOUR GEOMETRY

Many often mutually exclusive tour geometry's are required in order to satisfy the wide ranging Cassini science objectives. The tour designer's task is to satisfy as many of these often conflicting requirements as possible while also meeting other mission and ground system constraints. Many of the science instruments have specific viewing requirements which translate into required geometry's to be achieved during the tour some of which are time dependent. This section illustrates how some of the science requirements have driven the current tour designs. A detailed discussion of all science requirements and desired tour geometry's is beyond the scope of this paper, but a detailed list of geometry's desired by the atmospheres, rings, magnetospheric and plasma, and surface Cassini science working groups can be found in Reference 10. Only those requirements which were the hardest to achieve are referred to as "must have" tour geometry's. Failure to mention a specific science requirement or tour geometry does not mean it is of lower importance or priority, only that it can most likely be achieved by many tour designs.

Many required tour geometry's are specified in terms of orbit orientation (Figure 1) and inclination. Key "must have "tour geometry's are illustrated in Figure 4. The four Saturn centered orbits labeled "Phase I" to "Phase IV" in Figure 4 indicate the time order in which these types of orbits are achieved in the tours presented in this paper. Note that the viewpoint in this and many other figures in this paper is from the Saturn North pole with the direction to the Sun always towards the top of the frame. This frame is therefore noninertial and rotates with the apparent motion of the Sun. The orbits of Titan (orbital radius ~20 Rs) and Iapetus (orbital radius ~60 Rs) are shown for scale.

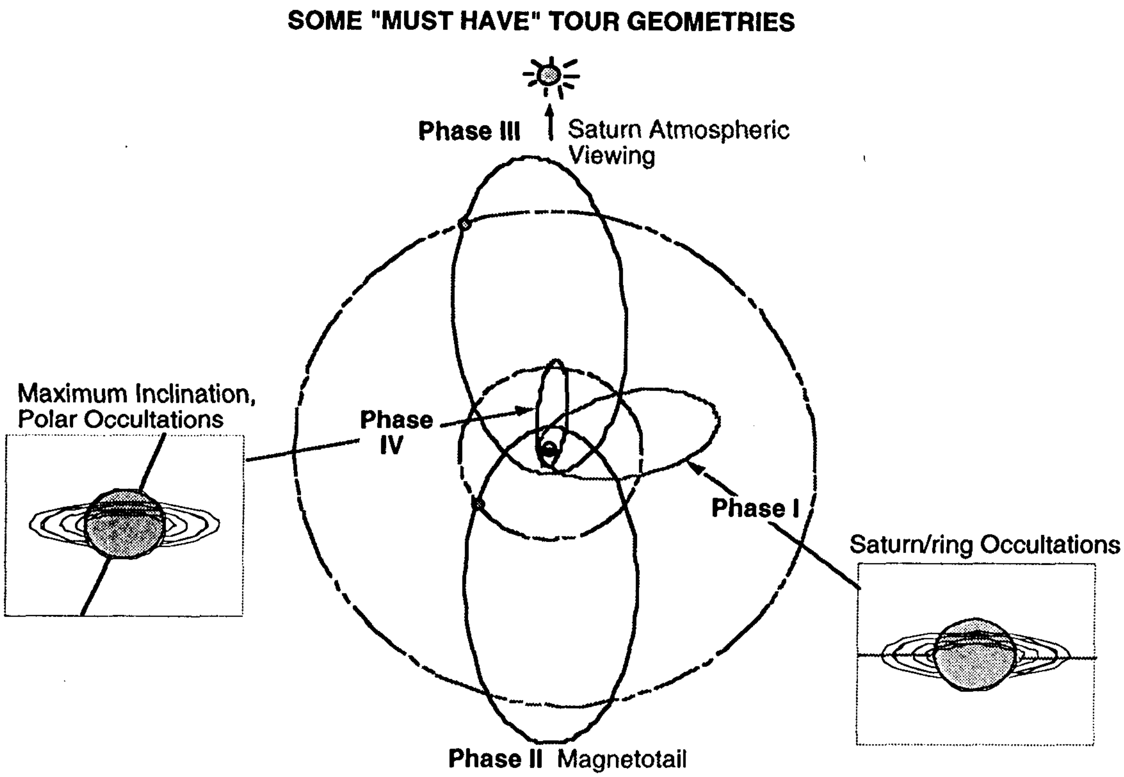


Figure 4 Some "Must Have" Tour Geometry's

Saturn/Ring Occultations

The orbit labeled "PHASE I" in Figure 4 illustrates the geometry required to achieve occultations of Saturn and its rings as viewed from the Earth or Sun. Radio occultations are obtained as the spacecraft passes behind Saturn and the entire ring plane as viewed by Earth (see inset on right of figure). These measurements are crucial for determination of ring properties and are one of the highest science priorities of the mission. To achieve this geometry, the line of nodes of the spacecraft orbit must be nearly perpendicular to the Saturn to Earth direction, and the orbit must be inclined by an amount equal to the declination of the Earth with respect to the Saturn equatorial plane which is about -24° at SOI[3]. During the 4 year tour, the tilt of the rings as viewed by Earth decreases to near zero by the end of mission such that the rings are nearly edge on as viewed from Earth. The quality of the occultation measurement s degrades significantly as the ring tilt decreases since differentiation between the rings disappears when the rings are viewed edge on. Therefore, the equatorial ring occultations are desired as soon as possible during the mission. Also note that the orientation of the "PHASE I" orbit is such that apoapsis is over the dawn terminator of Saturn which is similar in orientation to that of the initial orbit (Figure 2).

Magnetotail Passage

Another "must have" tour geometry is a passage through the Saturn magnetotail region. The definition of the magnetotail region is complex but, to first order, is achieved by passage of the spacecraft at an orbit orientation within 20° of local midnight at a distance ≥40 Rs. This type of orbit is depicted by the "PHASE II" orbit in Figure 4. An orbit inclination of a few degrees is required to pierce the current best estimate of the magnetotail, but a distant equatorial orbit satisfies the required magnetotail observational geometry. Note that the phase II orbit orientation differs by about 90° from the phase I orientation. Two general methods are employed to change orbit orientation in Cassini tours and these will be discussed in detail in subsequent sections.

Saturn Atmospheric Viewing

Observations of the illuminated disk of Saturn at low phase angle (<45°) from a large distance (>40 Rs) is required for atmospheric observations. A large distance is required in order to orient the narrow angle camera field of view within that of the wide angle camera. An orbit satisfying this geometry is labeled as "PHASE III" in Figure 4. Note that the orientation of this orbit is 180° away from that of the phase II magnetotail orbit. It takes a considerable number of Titan gravity assists and nearly a year in order to rotate apoapsis from the magnetotail orientation to the atmosphere viewing orientation. Therefore, incorporating both orientations in a 4 year tour represents a major challenge.

Highly Inclined Orbits

Several key science observations require highly inclined orbits characterized by an orbital inclination greater than 65° and preferably beyond 70°. Inclined orbits are required to observe the ring plane which is obviously of high priority to the Cassini mission but are also required to observe the high latitude Saturn aurora and kilometric radiation, and to obtain radio occultations of the polar region of Saturn's atmosphere. High inclination orbits also provide the best geometry for stellar occultations. An orbit satisfying this geometry is depicted by the "PHASE IV" orbit in Figure 4.

This sequence of Titan flybys is referred to as the "maximum inclination" sequence since the goal is to raise inclination to the maximum value possible. Such high inclination orbits are characterized by short period orbits resulting in apoapsis distances near the orbit of Titan. Other sequences in the tour achieve significant inclinations but none as high as in this sequence. The inset at the left of the Figure 4 illustrates the polar occultation track of the spacecraft as it passes behind Saturn. Polar occultations can also be obtained from similar orbits whose apoapsis lies near local midnight, but the distance between Saturn and the spacecraft is near 20 Rs which degrades the measurement. The majority of low periapsis radius (~2.7 Rs) orbits occur at the maximum inclination attained at the end of the sequence. These orbits are highly valued for magnetospheric observations.

Icy Satellite Flybys

Seven close flybys of Saturn's icy satellites, that is satellites other than Titan, are required during the tour. These flybys are also "must have" observations but aren't shown in Figure 4 because most can be obtained from a variety of orbits in different orientations. The desired satellites in their order of priority are Enceladus-1, Iapetus, Enceladus-2, Dione, Hyperion, Rhea, and Enceladus-3[10]. Note that 3 targeted Enceladus flybys are required since

Enceladus is an intriguing satellite since it is the brightest body in the solar system and is thought by some to be geologically active. Icy satellite flyby altitudes typically range from 500 to 1000 km and solar phase angle is required to be between 15° to 60° for at least one hour near closest approach.

Since Titan is the only satellite massive enough to provide sufficient gravity assist to shape the orbit, flybys of the icy satellites must be obtained on orbits which are already targeted to return to Titan. There are therefore far fewer targeted icy satellite flybys than Titan flybys in any tour. Also, a spacing of 16 days between any two satellite flybys must be maintained to meet ground system requirements which further reduces the number of flybys which can be considered targeted. However, dozens of distant (<100,000 km) nontargeted icy satellite flybys occur in most tours providing data not obtained during the close flybys.

Iapetus is another high science priority but only one close flyby is planned since it is generally the most difficult icy satellite to incorporate. Remote sensing of the light/dark boundary, which generally coincides with the boundary between the leading and trailing hemispheres of Iapetus, from an asymptote is required in order to study this region in depth. Iapetus is a very unusual satellite in that the leading hemisphere is very dark while the trailing hemisphere is light. This requirement requires that Iapetus be encountered within ~45° of the Sun to Saturn direction. If the Sun-Saturn-Iapetus angle is near 90°, the light/dark boundary coincides with the terminator and can't be imaged at the desired phase angles.

General Strategy for T9 and T18 Tours

Of the 18 tour classes evaluated, only a small number had the potential to achieve all the "must have" tour geometry's (Figure 4) in a 4 year tour. This section outlines the strategy adopted for accomplishing these tour objectives. Note that only science objectives which were among the hardest to achieve are discussed.

Since changing orbit orientation requires Titan gravity assists and time, the first tour objective accomplished was the required Saturn/ring occultations since the dawn orbit orientation required ("PHASE I" orbit in Figure 4) is similar in orientation to that of the initial orbit (Figure 2). Also , the ring occultations measurements degrade with time during the tour due to the decreasing tilt of the rings as viewed from Earth. Seven Saturn/ring occultations were achieved in the latter part of the first year of the tours described in this paper.

Upon completion of the occultation sequence at the end of the first year of the tour, the next decision was in which direction to change the orbit orientation. The apoapsis of the orbit can be "rotated" clockwise to the magnetotail (midnight) orientation or counter-clockwise to the atmospheric viewing orientation. After construction and evaluation of the 18 classes of tours[11], it was clear that all the "must have" tour objectives could not be accomplished in a tour which rotates counter-clockwise. Saturn's 29.5 year orbital period causes the orbit orientation in a Sun-relative frame such as Figure 4 to rotate clockwise by ~12°/month. This "free rotation" of the Sun results in a cumulative orbit orientation change of ~49° at the end of any 4 year tour. Rotating spacecraft orbit apoapsis counter-clockwise fights this free rotation and takes longer than rotating clockwise. The orbit orientation is therefore rotated clockwise during the second and third years of the tour to achieve the orbit orientations required for magnetotail (phase II) and atmospheric (phase III) observations as shown in Figure 4.

During the fourth year of the tour, the maximum inclination sequence raises inclination to beyond 70°. Placing the maximum inclination sequence at the end of the tour is the most time efficient way to accomplish this objective. About 10 months is required to raise inclination from near zero to beyond 70°. If this sequence were placed in the middle of the tour, an additional 10 months would be required to decrease inclination back to zero. There is insufficient time to increase inclination to the maximum value possible and then back to the original value and also accomplish the other mission objectives. Note that the phase IV orbits must have their ascending or descending nodes near the Saturn to Sun direction which requires a near noon orbit orientation. Therefore, a progression from noon orientation atmospheric viewing to the maximum inclination sequence is time efficient.

The Saturn-relative tour geometry's for each phase and year of the tour are summarized in Table 1. Note that each phase is about 1 year in duration. The tour phases and objectives are the same for all three tours but are accomplished by different means and to different levels of success. Orbit orientation change is accomplished by either equatorial rotation or a 180° transfer. Both methods will be discussed in detail in subsequent sections.

Table 1 Saturn Relative Tour Objectives

Phase, Year	Primary Saturn Orbit Objective	T9-1 Sequences	T18-4 Sequences	T18-5 Sequences
I, Year-1	Initial orbit, Saturn/ring occultations	individual flybys	individual flybys	individual flybys
II, Year-2	Rotate apoapsis to magnetotail	180° Transfer	Equatorial Rotation	Equatorial Rotation
III, Year-3	Rotate apoapsis to noon	180° Transfer	180° Transfer	180° Transfer
IV, Year-4	Maximize orbit inclination	Maximum Inclination	Maximum Inclination	Maximum Inclination

TOUR CHARACTERISTICS

The time history of events and key characteristics of the T9-1, T18-4, and T18-5 tours are described in this section. Table 2 summarizes the number of occurrences of particular events in each tour. Note the number of Sun occultations are similar to the number of Earth occultations. Targeted flybys are those whose satellite relative aimpoints are controlled through the use of maneuvers and tend to have low flyby altitudes. The aimpoints for nontargeted flybys are not controlled and tend to be more distant. Data illustrating the Saturn-centered orbit evolution which results from modification of the spacecraft trajectory primarily by Titan gravity assists is presented first. Data relative to the satellite encounters is then presented.

Table 2 Tour Characteristics

Tour	Number of Revs About Saturn	Number Targeted Titan Flybys	Number Targeted Icy Satellite Flybys	Number Nontargeted Icy Satellite Flybys	Number of Saturn Earth Occultations	Number of Titan Earth Occultations
T9-1	78	51	9	36	42	18
T18-4	71	39	7	35	41	14
T18-5	72	44	7	27	33	17

Tables 3 to 5 summarize in tabular format the characteristics of the T9-1, T18-4, and T18-5 tours, respectively. Each line corresponds to a targeted satellite encounter and each of the 4 tour phases are delineated. For example, in Table 3, the flyby labeled "Titan-6" is the 6th Titan flyby of the tour and occurs on August 22, 2005 which is 1.14 years past the start of the tour (tour begins July 1, 2004). This flyby is outbound from Saturn closest approach (as opposed to inbound) and is characterized by an altitude at closest approach of 950 km and a B-plane angle with respect to the Titan equator of 105° indicating that the flyby passes under the south polar region of Titan. The next satellite flyby occurs 15.9 days later after exactly 1 revolution about Saturn. After the Titan-6 flyby, the orbit period is 16.0 days, orbit inclination is 7.7°, distance from the center of Saturn to the ascending node in the Saturn equatorial plane is 2.8 Saturn radii (1Rs=60,330 km) and distance to the descending node is 19.8 Rs. The orbit orientation is 76° indicating that at orbit apoapsis, the spacecraft observes the dawn terminator of Saturn (Figure 1).

Note that data for the first 1.2 years of the tour are identical - this phase of the tour will remain part of any future Cassini tour by Project decree. The distance to the nodes (Ran, Rdn) is constrained to be greater than 2.6 Rs to avoid potentially hazardous ring particle regions. Since Titan orbits at about 20 Rs from Saturn, for inclined orbits, either the ascending or descending node must be near 20 Rs. Note that the tours are comprised of mostly Titan flybys since only Titan has sufficient gravity assist to significantly alter the trajectory. This is demonstrated in the tables by the fact that the post-flyby orbital elements do not change significantly after icy satellite flybys. The tables also demonstrate that the spacecraft often makes more than one rev between flybys. For example, Table 5 shows that the orbit period after the "Titan-42" flyby is 9.6 d but the time between flybys is ~48 d.

Table 3 T9-1 Tour Profile

Encounter	Date YMMDD.HHMM GMT	Years From Start	In/ Out-Bound	Alt. (km)	B-plane Angle (°)	Time Flight (d)	Revs	Period (d)	Inc. (°)	Ran (Rs)	Rdn (Rs)	Orienta-tion (°)
Phase I												
Titan-1	41127.1415	.41	I	1200	-24	47.8	1.0	47.9	15.5	19.5	9.0	79
Titan-2	50114.1006	.54	I	1200	-60	31.9	1.0	31.9	7.3	19.2	6.3	74
Titan-3	50215.0721	.63	I	1194	-37	22.1	1.1	20.4	.3	3.7	33.1	65
Enceladu-1	50309.0925	.69	I	500	150	22.4	1.1	20.5	.3	3.7	32.6	66
Titan-4	50331.1941	.75	O	2591	-148	16.0	1.0	16.0	6.9	2.8	21.3	72
Titan-5	50416.1855	.79	O	950	-76	89.0	4.9	18.2	21.5	3.9	20.9	66
Enceladu-2	50714.2000	1.04	I	1000	-160	38.5	2.1	18.3	21.8	4.0	20.8	68
Titan-6	50822.0856	1.14	O	950	105	16.0	1.0	16.0	7.7	2.8	19.8	76
Phase II												
Titan-7	50907.0819	1.19	O	3621	54	18.7	1.0	18.4	.3	7.7	4.6	74
Hyperion-1	50926.0135	1.24	O	1000	180	15.7	.9	18.2	.2	6.1	5.4	74
Dione-1	51011.1802	1.28	I	500	8	16.4	.9	18.0	.2	6.3	5.2	74
Titan-8	51028.0433	1.33	I	950	-72	15.9	1.0	16.0	16.1	3.1	20.4	75
Titan-9	51113.0311	1.37	I	950	-83	15.9	1.0	16.0	30.2	3.9	20.2	80
Titan-10	51129.0138	1.41	I	950	-77	15.9	1.0	16.0	40.6	5.4	20.1	86
Titan-11	51215.0007	1.46	I	950	-72	15.9	1.0	16.0	47.9	7.6	20.1	92
Titan-12	51230.2239	1.50	I	950	-65	15.9	1.0	16.0	52.8	10.4	20.1	99
Titan-13	60115.2112	1.54	I	950	-57	15.9	1.0	16.0	56.0	13.6	20.0	107
Titan-14	60131.1945	1.59	I	950	-47	15.9	1.0	16.0	58.0	16.9	20.0	115
Titan-15	60216.1829	1.63	I	6806	-79	23.6	1.3	17.9	57.2	20.3	20.0	131
Titan-16	60312.0941	1.70	O	950	-52	15.9	1.0	16.0	56.7	20.3	14.3	211
Titan-17	60328.0815	1.74	O	950	-48	15.9	1.0	16.0	53.7	20.3	11.0	205
Titan-18	60413.0648	1.78	O	950	-60	15.9	1.0	16.0	49.1	20.2	8.0	200
Titan-19	60429.0520	1.83	O	950	-68	15.9	1.0	16.0	42.0	20.1	5.7	197
Titan-20	60515.0353	1.87	O	950	-75	15.9	1.0	16.0	31.7	19.9	4.0	198
Titan-21	60531.0231	1.91	O	950	-81	16.0	1.0	16.0	17.4	19.4	3.1	201
Titan-22	60616.0125	1.96	O	950	-86	16.0	1.0	16.0	.5	3.4	8.4	207
Titan-23	60702.0042	2.00	O	1698	2	21.8	.9	23.8	.6	9.3	6.2	198
Tethys-1	60723.1910	2.06	I	500	0	24.4	1.0	23.7	.6	7.6	7.3	199
Rhea-1	60817.0458	2.13	O	500	-62	21.4	.9	24.2	.4	6.8	8.3	199

Table 3 T9-1 Tour Profile (continued)

Encounter	Date YMMDD.HHMM GMT	Years From Start	In/ Out-Bound	Alt. (km)	B-plane Angle (°)	Time Flight (d)	Revs	Period (d)	Inc. (°)	Ran (Rs)	Rdn (Rs)	Orientation (°)
Phase III												
Titan-24	60907.1355	2.19	I	950	-28	16.0	1.0	16.0	9.4	2.7	19.7	169
Titan-25	60923.1254	2.23	I	950	-84	15.9	1.0	16.0	25.9	3.4	20.3	178
Titan-26	61009.1130	2.27	I	950	-79	15.9	1.0	16.0	38.4	4.6	20.5	187
Titan-27	61025.0959	2.32	I	950	-73	15.9	1.0	16.0	47.2	6.6	20.6	196
Titan-28	61110.0830	2.36	I	950	-66	15.9	1.0	16.0	53.0	9.2	20.7	205
Titan-29	61126.0702	2.40	I	950	-58	15.9	1.0	16.0	56.9	12.4	20.7	214
Titan-30	61212.0535	2.45	I	950	-49	15.9	1.0	16.0	59.4	15.7	20.7	222
Titan-31	61228.0417	2.49	I	5239	-80	23.9	1.3	18.2	58.5	19.6	20.7	240
Titan-32	70121.0045	2.56	O	950	-55	15.9	1.0	16.0	58.1	19.6	14.9	265
Titan-33	70205.2321	2.60	O	950	-47	15.9	1.0	16.0	55.5	19.7	11.7	274
Titan-34	70221.2155	2.64	O	950	-58	15.9	1.0	16.0	51.5	19.7	8.8	282
Titan-35	70309.2029	2.69	O	950	-66	15.9	1.0	16.0	45.8	19.7	6.4	290
Titan-36	70325.1901	2.73	O	950	-73	15.9	1.0	16.0	37.6	19.7	4.7	297
Titan-37	70410.1734	2.78	O	950	-78	15.9	1.0	16.0	26.3	19.7	3.5	303
Titan-38	70426.1613	2.82	O	950	-84	16.0	1.0	16.0	11.7	19.7	2.9	307
Titan-39	70512.1506	2.86	O	950	-88	16.0	1.0	16.0	4.8	2.8	19.6	310
Titan-40	70528.1413	2.91	O	1663	20	19.4	.8	22.9	.4	47.5	3.8	299
Titan-41	70616.2355	2.96	I	2351	-177	36.8	1.0	35.2	.3	21.2	6.2	312
Dione-2	70723.1951	3.06	I	548	-176	38.4	1.1	36.5	.3	20.8	6.2	313
Phase IV												
Titan-42	70831.0625	3.17	O	3663	-106	10.3	.3	32.4	6.5	5.9	19.7	317
Iapetus-1	70910.1323	3.19	O	1000	172	21.6	.7	32.0	6.4	5.7	19.2	318
Titan-43	71002.0429	3.25	O	950	-122	47.8	2.0	23.9	17.9	4.9	19.5	327
Titan-44	71119.0028	3.38	O	950	-160	16.0	1.0	16.0	26.2	3.4	19.4	339
Titan-45	71204.2317	3.43	O	950	-100	15.9	1.0	16.0	37.7	4.6	19.6	335
Titan-46	71220.2148	3.47	O	950	-165	47.8	4.0	11.9	46.6	3.6	19.6	344
Titan-47	80206.1719	3.60	O	950	-138	31.9	3.0	10.6	55.7	4.2	19.6	16
Titan-48	80309.1411	3.69	O	3716	-168	16.9	1.8	9.6	60.1	3.9	19.7	14
Enceladu-3	80326.1146	3.74	I	1000	90	30.9	3.2	9.6	60.1	3.9	19.6	14
Titan-49	80426.0943	3.82	O	950	168	15.9	2.0	8.0	67.0	3.0	19.6	13
Titan-50	80512.0803	3.86	O	950	-133	15.9	2.0	8.0	70.1	4.2	19.7	15
Titan-51	80528.0630	3.91	O	950	90	33.8	4.8	7.0	72.3	2.2	19.5	15

Table 4 T18-4 Tour Profile

Encounter	Date YMMDD.HHMM GMT	Years From Start	In/ Out-Bound	Alt. (km)	B-plane Angle (°)	Time Flight (d)	Revs	Period (d)	Inc. (°)	Ran (Rs)	Rdn (Rs)	Orientation (°)
Phase I												
Titan-1	41127.1415	.41	I	1200	-24	47.8	1.0	47.9	15.5	19.5	9.0	79
Titan-2	50114.1006	.54	I	1200	-60	31.9	1.0	31.9	7.3	19.2	6.3	74
Titan-3	50215.0721	.63	I	1194	-37	22.1	1.1	20.4	.3	3.7	33.1	65
Enceladu-1	50309.0925	.69	I	500	150	22.4	1.1	20.5	.3	3.7	32.6	66
Titan-4	50331.1941	.75	O	2591	-148	16.0	1.0	16.0	6.9	2.8	21.3	72
Titan-5	50416.1855	.79	O	950	-76	89.0	4.9	18.2	21.5	3.9	20.9	66
Enceladu-2	50714.2000	1.04	I	1000	-160	38.5	2.1	18.3	21.8	4.0	20.8	68
Titan-6	50822.0856	1.14	O	950	105	16.0	1.0	16.0	7.7	2.8	19.8	76
Phase II												
Titan-7	50907.0807	1.19	O	3850	53	18.7	1.0	18.4	.3	8.0	4.5	74
Hyperion-1	50926.0116	1.24	O	1000	180	15.7	.9	18.2	.2	6.3	5.4	74
Dione-1	51011.1807	1.28	I	500	8	16.4	.9	18.0	.2	6.3	5.3	74
Titan-8	51028.0441	1.33	I	1483	-179	29.8	1.0	28.5	.4	5.1	25.8	88
Rhea-1	51126.2257	1.41	I	500	-18	29.8	1.1	27.5	.3	4.9	33.6	88
Titan-9	51226.1904	1.49	O	10576	179	19.7	.8	23.4	.4	4.1	36.8	94
Titan-10	60115.1212	1.54	I	2045	-179	42.9	1.1	39.3	.4	5.6	67.2	107
Titan-11	60227.0905	1.66	O	1764	180	19.6	.8	23.3	.4	3.8	45.4	122
Titan-12	60318.2344	1.71	I	1888	-179	42.9	1.1	39.3	.4	5.6	46.3	135
Titan-13	60430.2135	1.83	O	1781	180	19.6	.8	23.3	.4	4.5	15.0	148
Phase III												
Titan-14	60520.1133	1.88	I	950	-33	15.9	1.0	16.0	10.8	2.6	20.4	141
Titan-15	60605.0951	1.93	I	950	-84	15.9	1.0	16.0	27.4	3.2	20.5	145
Titan-16	60621.0803	1.97	I	950	-79	15.9	1.0	16.0	39.9	4.4	20.5	147
Titan-17	60707.0624	2.02	I	950	-73	15.9	1.0	15.9	48.4	6.3	20.6	148
Titan-18	60723.0451	2.06	I	1160	-24	63.8	5.0	12.8	56.3	6.0	20.6	142
Titan-19	60924.2325	2.23	I	3055	-149	15.9	1.0	15.9	52.8	8.1	20.7	149
Titan-20	61010.2148	2.28	I	950	-128	47.8	2.0	24.0	50.1	13.8	20.6	212
Titan-21	61127.1744	2.41	I	2846	-139	39.7	1.1	35.5	47.8	19.7	20.6	222
Titan-22	70106.0934	2.52	O	950	-79	31.9	1.0	32.0	44.3	19.7	14.5	233
Titan-23	70207.0650	2.60	O	950	-74	31.9	1.0	31.9	38.6	19.7	10.8	242
Titan-24	70311.0359	2.69	O	1734	-113	47.8	2.0	23.9	35.7	19.7	7.2	256
Titan-25	70427.2349	2.82	O	950	-141	15.9	1.0	16.0	35.4	19.7	4.2	273
Titan-26	70513.2232	2.87	O	950	-80	15.9	1.0	16.0	22.8	19.5	3.1	277
Titan-27	70529.2119	2.91	O	950	-85	16.0	1.0	16.0	7.0	18.9	2.6	280
Titan-28	70614.2022	2.95	O	950	-90	16.0	1.0	16.0	10.1	2.7	20.5	282
Titan-29	70630.1931	3.00	O	950	37	19.4	.8	22.9	.4	30.9	3.8	271
Titan-30	70720.0431	3.05	I	1366	179	43.2	1.1	39.6	.5	67.4	5.4	286
Phase IV												
Titan-31	70901.0837	3.17	O	2725	117	17.6	.6	32.0	7.7	21.3	5.7	290
Iapetus-1	70918.2344	3.22	I	500	-167	14.2	.4	32.4	7.5	21.2	6.1	292
Titan-32	71003.0338	3.26	O	1237	126	47.8	2.0	23.9	17.9	20.3	5.2	298
Titan-33	71119.2334	3.39	O	950	157	15.9	1.0	16.0	26.7	20.0	3.7	309
Titan-34	71205.2219	3.43	O	950	102	15.9	1.0	16.0	37.9	20.0	5.1	304
Titan-35	71221.2049	3.47	O	1056	168	21.7	1.8	11.9	46.0	19.9	3.9	314
Enceladu-3	80112.1410	3.53	I	500	-179	26.1	2.2	12.0	46.0	19.9	3.9	315
Titan-36	80207.1612	3.60	O	950	139	31.9	3.0	10.6	54.8	19.8	4.5	318
Titan-37	80310.1310	3.69	O	995	163	63.8	7.0	9.1	61.9	19.8	4.3	326
Titan-38	80513.0713	3.87	O	950	174	15.9	2.0	8.0	67.7	19.8	4.0	335
Titan-39	80529.0537	3.91	O	2685	-127	32.9	4.6	7.1	70.8	19.7	2.7	341

Table 5 T18-5 Tour Profile

Encounter	Date YMMDD.HHMM GMT	Years From Start	In/ Out-Bound	Alt. (km)	B-plane Angle (°)	Time Flight (d)	Revs	Period (d)	Inc. (°)	Ran (Rs)	Rdn (Rs)	Orienta-tion (°)
Phase I												
Titan-1	41127.1415	.41	I	1200	-24	47.8	1.0	47.9	15.5	19.5	9.0	79
Titan-2	50114.1006	.54	I	1200	-60	31.9	1.0	31.9	7.3	19.2	6.3	74
Titan-3	50215.0721	.63	I	1194	-37	22.1	1.1	20.4	.3	3.7	33.1	65
Enceladu-1	50309.0925	.69	I	500	150	22.4	1.1	20.5	.3	3.7	32.6	66
Titan-4	50331.1941	.75	O	2591	-148	16.0	1.0	16.0	6.9	2.8	21.3	72
Titan-5	50416.1855	.79	O	950	-76	89.0	4.9	18.2	21.5	3.9	20.9	66
Enceladu-2	50714.2000	1.04	I	1000	-160	38.5	2.1	18.3	21.8	4.0	20.8	68
Titan-6	50822.0856	1.14	O	950	105	16.0	1.0	16.0	7.7	2.8	19.8	76
Phase II												
Titan-7	50907.0812	1.19	O	4105	51	18.7	1.0	18.4	.3	8.0	4.5	74
Hyperion-1	50926.0127	1.24	O	1000	180	15.7	.9	18.2	.2	6.3	5.3	74
Dione-1	51011.1807	1.28	I	500	8	16.4	.9	18.0	.2	6.3	5.3	74
Titan-8	51028.0436	1.33	I	1469	-179	29.8	1.0	28.5	.4	4.8	41.7	88
Rhea-1	51126.2251	1.41	I	500	16	29.9	1.1	27.5	.4	4.9	32.6	88
Titan-9	51226.1921	1.49	O	10458	179	19.7	.8	23.4	.4	4.1	36.0	93
Titan-10	60115.1216	1.54	I	2053	-179	42.9	1.1	39.2	.4	5.6	66.9	107
Titan-11	60227.0854	1.66	O	1813	180	19.7	.8	23.4	.4	3.9	45.7	121
Titan-12	60319.0033	1.71	I	1949	-179	42.9	1.1	39.2	.4	5.7	46.6	135
Titan-13	60430.2126	1.83	O	1851	-179	19.6	.8	23.4	.4	4.1	23.3	148
Titan-14	60520.1245	1.88	I	1879	-179	42.9	1.1	39.2	.4	6.5	22.5	159
Titan-15	60702.0945	2.00	O	1909	179	19.6	.8	23.4	.4	6.6	7.6	164
Phase III												
Titan-16	60722.0057	2.06	I	950	-90	47.8	2.0	24.0	15.0	4.8	20.1	188
Titan-17	60907.2038	2.19	I	950	-23	15.9	1.0	16.0	25.0	3.2	20.5	172
Titan-18	60923.1914	2.23	I	950	-79	15.9	1.0	16.0	37.9	4.3	20.5	173
Titan-19	61009.1742	2.27	I	950	-73	15.9	1.0	15.9	46.9	6.2	20.6	194
Titan-20	61025.1610	2.32	I	950	-10	47.8	4.0	12.0	55.5	5.0	20.7	164
Titan-21	61212.1154	2.45	I	950	-120	15.9	1.0	16.0	53.3	8.9	20.7	204
Titan-22	61228.1018	2.49	I	950	-59	15.9	1.0	16.0	57.2	12.0	20.7	212
Titan-23	70113.0851	2.54	I	950	-50	15.9	1.0	16.0	59.7	15.3	20.7	221
Titan-24	70129.0730	2.58	I	3862	-72	23.8	1.3	18.1	59.0	19.6	20.7	239
Titan-25	70222.0324	2.64	O	950	-54	15.9	1.0	16.0	58.8	19.7	15.0	263
Titan-26	70310.0200	2.69	O	962	-47	15.9	1.0	16.0	56.2	19.7	11.8	272
Titan-27	70326.0035	2.73	O	950	-57	15.9	1.0	16.0	52.4	19.7	8.9	280
Titan-28	70410.2308	2.78	O	950	-65	15.9	1.0	16.0	46.9	19.7	6.5	287
Titan-29	70426.2142	2.82	O	950	-72	15.9	1.0	16.0	39.0	19.7	4.7	294
Titan-30	70512.2019	2.86	O	3624	-77	15.9	1.0	16.0	32.9	19.5	3.9	297
Titan-31	70528.1856	2.91	O	950	-81	16.0	1.0	16.0	20.0	19.7	3.0	302
Titan-32	70613.1746	2.95	O	950	-86	16.0	1.0	16.0	4.1	19.5	2.6	306
Titan-33	70629.1700	2.99	O	1782	-15	19.3	.8	22.8	.3	32.1	3.7	296
Titan-34	70719.0041	3.05	I	1304	-178	43.2	1.1	39.7	.3	25.0	6.2	311
Phase IV												
Titan-35	70831.0633	3.17	O	3197	-115	10.2	.3	32.5	6.6	5.9	19.5	318
Iapetus-1	70910.1218	3.19	O	1000	160	21.7	.7	32.0	6.2	5.7	17.7	319
Titan-36	71002.0505	3.25	O	950	120	47.8	2.0	23.9	4.9	22.9	4.1	325
Titan-37	71119.0110	3.38	O	950	157	16.0	1.0	16.0	12.4	20.8	2.6	335
Titan-38	71205.0040	3.43	O	950	96	16.0	1.0	16.0	27.5	20.3	3.2	329
Titan-39	71220.2336	3.47	O	950	101	15.9	1.0	16.0	39.0	20.0	4.4	322
Titan-40	80105.2209	3.51	O	950	169	47.8	4.0	11.9	47.8	19.9	3.4	329
Titan-41	80222.1735	3.65	O	950	140	19.1	1.8	10.6	56.9	19.9	3.9	329
Enceladu-3	80312.1906	3.70	I	1000	0	12.8	1.2	10.6	56.9	19.9	3.9	329
Titan-42	80325.1431	3.73	O	950	147	47.8	5.0	9.6	63.8	19.9	4.5	329
Titan-43	80512.1006	3.86	O	950	-161	15.9	2.0	8.0	70.1	19.8	3.3	335
Titan-44	80528.0829	3.91	O	1744	-166	33.8	4.7	7.2	75.2	19.8	2.7	22

Saturn Orbits

Views of each 4 year tour from both within and above the ring plane are shown in Figures 5 to 10 and demonstrate that the time history of orientation and inclination is consistent with the strategy outlined in Table 1. On the top half of the page, the viewpoint is from slightly above the ring plane from the noon orientation at the start of the tour. In the lower half of the page, the viewpoint is from the Saturn N. pole and the direction to the Sun is always at the top of the frame. The orbits of Titan (orbital radius ~20 Rs) and Iapetus (orbital radius ~60 Rs) are shown for scale.

Note that the orbits near the end of the third year of the tour never quite reach the desired noon orientation (phase III, Figure 4) at distances greater than 40 Rs due to lack of time. However, even though orbit apoapsis is not in the noon orientation, a significant portion of the rest of the orbit may provide required low phase angle viewing. The required dayside atmospheric viewing geometry (distance >40 Rs and phase angle <45°) is available for 56 d in T9-1, 0 d in T18-4, and 46 d in T18-5. Tour T18-4 is clearly less desirable from the atmospheric observations standpoint while T9-1 and T18-5 are provide substantial viewing time. Figure 11 overlays the T18-4 (solid lines) and T18-5 (dashed lines) tours for comparison.

Magnetotail coverage also varies considerably among the tours. The definition of the magnetotail is complex and somewhat uncertain but excursions >40Rs within ~20° of the Sun to Saturn line (midnight orientation) are required. Tour T18-5 has the deepest excursion at ~68 Rs (Figure 10) and T9-1 (Figure 6) also exceeds the requirement with a passage of ~49 Rs. However, T18-4 (Figures 8, 11) just grazes the deep magnetotail region and fails to meet this requirement. Also note from Figure 7 that the vertical excursion of the Saturn orbits is greater in T18-4 than the other two tours since larger period orbits are used during the inclined 180° transfer sequence.

The significant differences in the Saturn-centered "real estate" covered by T18-4 versus T18-5 (Figure 11) is due to the satellite encounter frequency difference between the two tours. T18-4 was designed to meet the ground system constraint which limits the number of consecutive short satellite-to-satellite transfer times which in turn reduces the number of Titan flybys available for gravity assist. Since fewer gravity assists are available to shape the trajectory and less time is available due to the increased spacing between flybys, T18-4 covers less of the Saturnian system than T18-5. However, T18-4 is less stressful to the ground system and is the only tour created to date which does not significantly violate one or more ground system constraints. Comparison between the T18-4 and T18-5 tours illustrates the relationship between science return and mission operability.

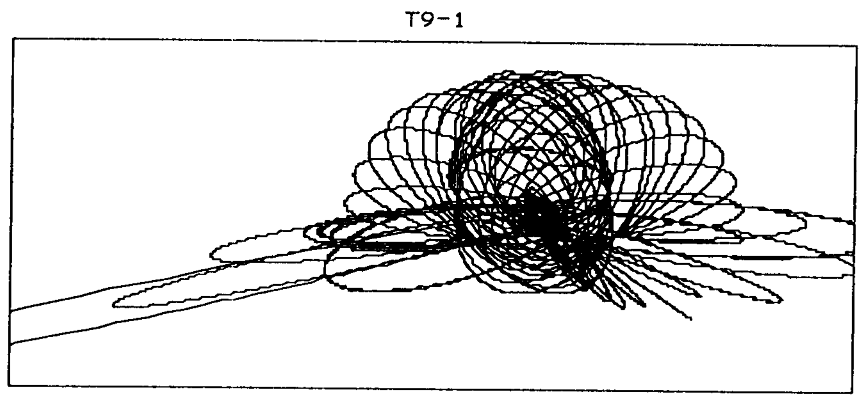


Figure 5 Tour T9-1: View at ~Noon Orientation From Just Above Ring Plane

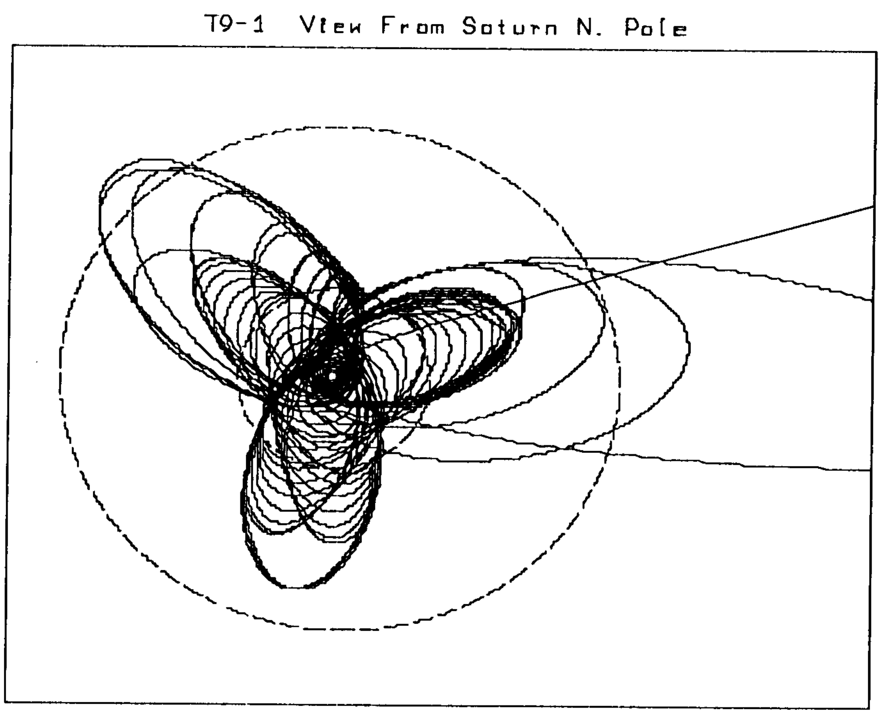


Figure 6 Tour T9-1: View From Saturn N. Pole (Direction to Sun Towards Top)

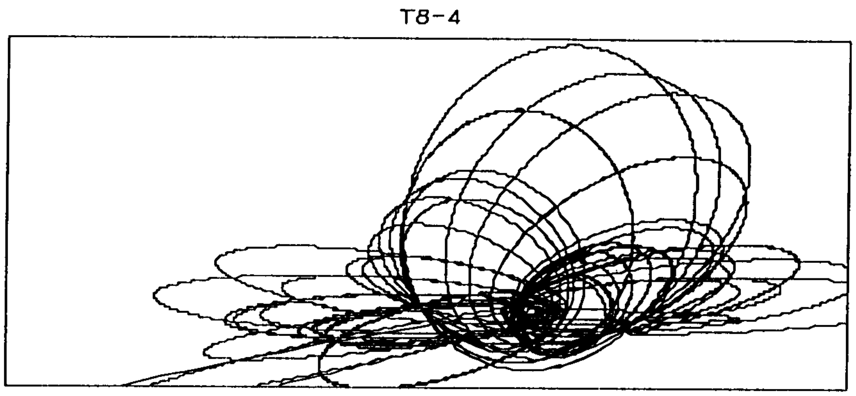


Figure 7 Tour T18-4: View at ~Noon Orientation From Just Above Ring Plane

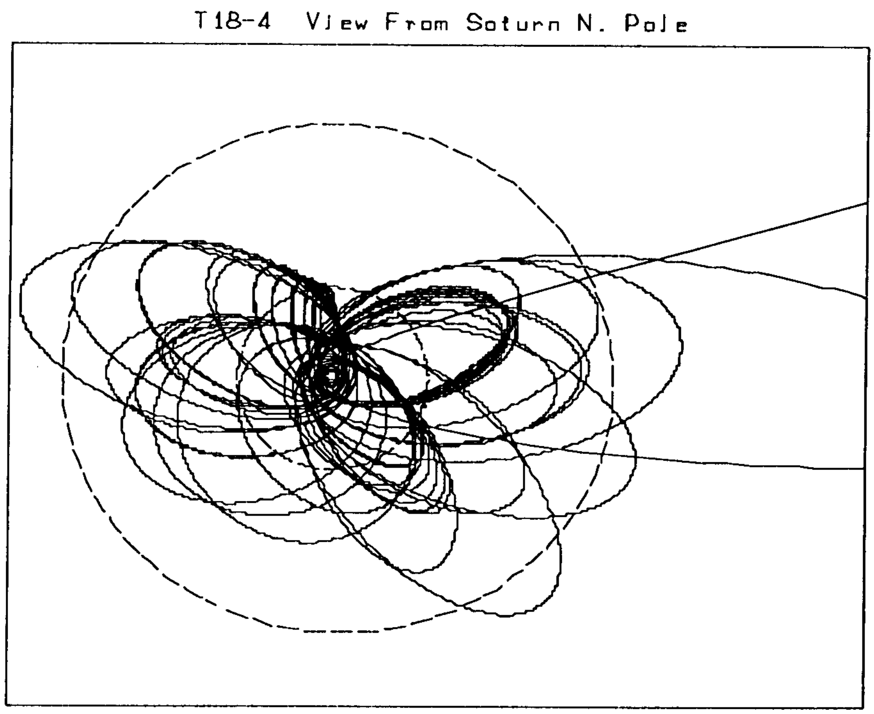


Figure 8 Tour T18-4: View From Saturn N. Pole (Direction to Sun Towards Top)

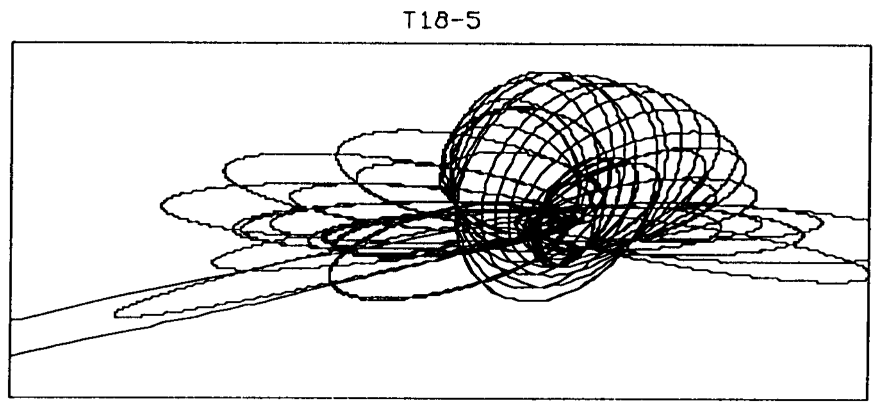


Figure 9 Tour T18-5: View at ~Noon Orientation From Just Above Ring Plane

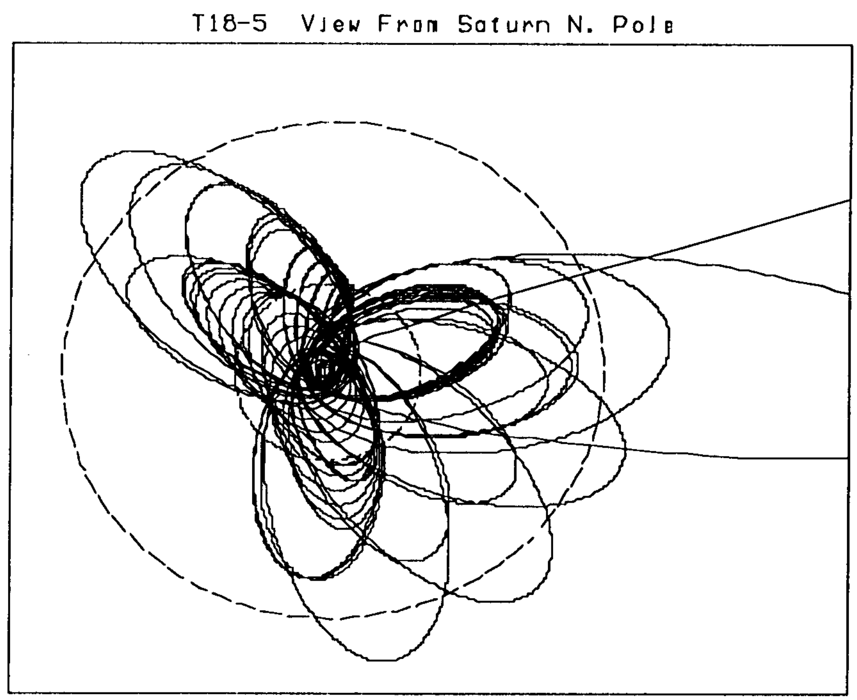


Figure 10 Tour T18-5: View From Saturn N. Pole (Direction to Sun Towards Top)

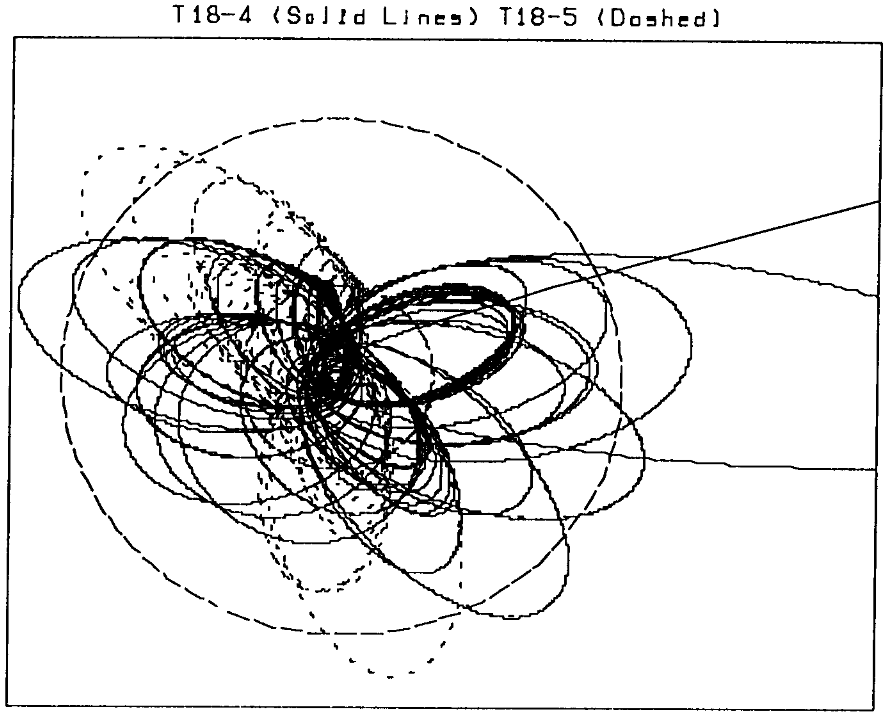


Figure 11 T18-4 Versus T18-5: View From Saturn N. Pole (Direction to Sun Towards Top)

Titan Flybys

Fortunately for Cassini tours, Titan is both the most visited and most scientifically interesting satellite. Even with the 39 to 51 Titan flybys comprising these three tours, allocations of Titan flybys are still hotly contested among the various science disciplines. In general, low altitude Titan flybys at the minimum permissible flyby altitude of 950 km are preferred. For example, the RADAR instrument can only perform synthetic aperture radar (SAR) mapping when the altitude is less than 1600 km and the INMS instrument can only gather in-situ measurements near the 950 km limit.

The aimpoint at each Titan flyby is dictated by the desired modification to the trajectory provided by the Titan gravity assist. Titan aimpoints are chosen to achieve the desired orbit orientation and inclination profile rather than to achieve a particular Titan flyby orientation. However, since there are so many Titan flybys, a significant portion of the surface can be observed and mapped by such instruments as the Cassini RADAR. Figures 12 to 14 are plots of the Titan ground tracks within 2 hours of closest approach. East longitudes are shown, points are plotted at 1 minute intervals, and the closest approach location is circled. The Probe touchdown location at ~18 N. latitude and ~209 E. longitude is well covered by all three tours.

The closest approach subspacecraft points are a direct function of the Titan aimpoint B-plane values in Tables 3 to 5. Aimpoints are targeted above Titan's northern hemisphere during all 180° transfer sequences. However, for the maximum inclination sequence, aimpoints are targeted above the northern hemisphere of Titan for T9-1 and under the southern hemisphere for the two T18 tours which accounts for the reduced southern hemisphere ground track coverage in T9-1 (Figure 12).

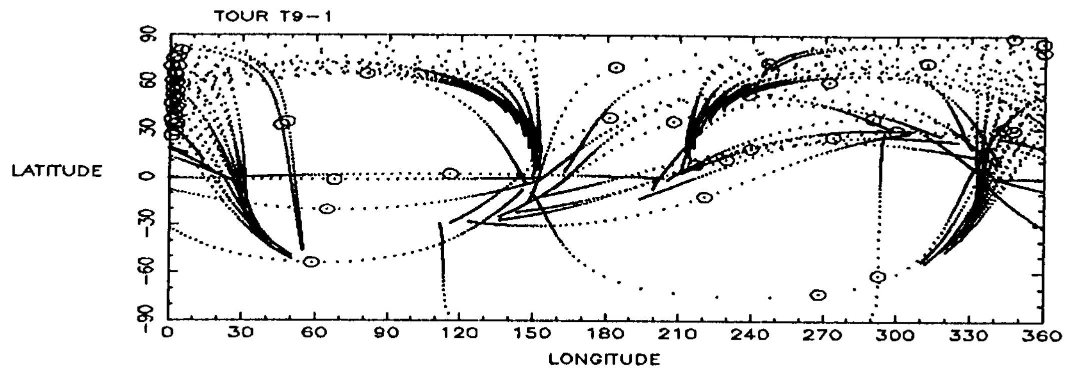


Figure 12 T9-1 Titan Ground Tracks (closest approach points circled)

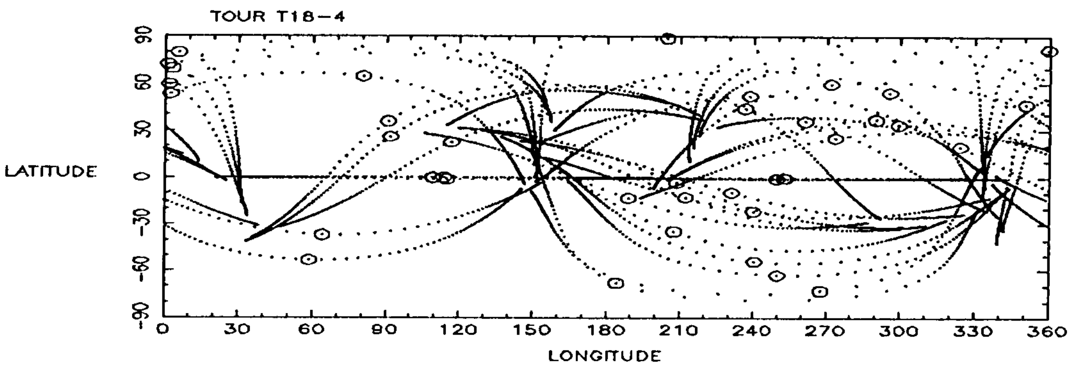


Figure 13 T18-4 Titan Ground Tracks (closest approach points circled)

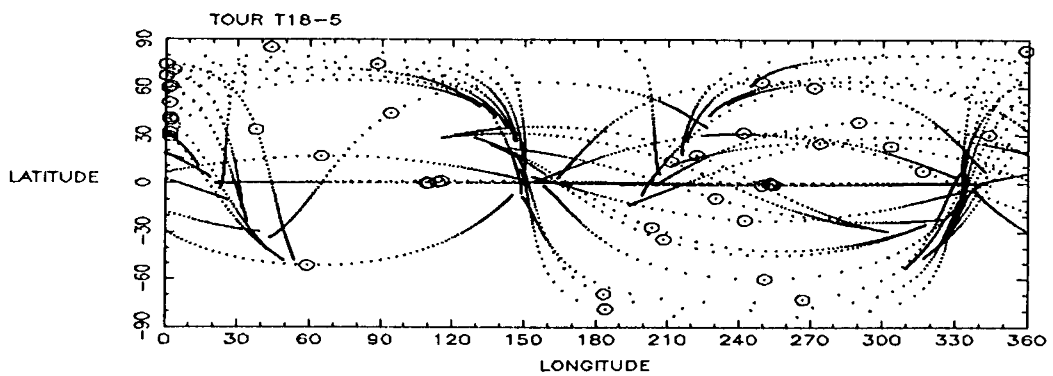


Figure 14 T18-5 Titan Ground Tracks (closest approach points circled)

Icy Satellite Flybys

All three tours contain the 7 required targeted icy satellite flybys, i.e., all tours contain three Enceladus flybys and one Dione, Rhea, Hyperion, and Iapetus flyby. Flyby altitudes range from 500 to 1000 km. The Dione, Hyperion, and first two Enceladus flybys are common to all three tours and are obtained in the first 1.3 years of the tour. The first year of the each tour contains two targeted Enceladus flybys (Figure 15) which will remain part of any future tour since this portion of the tour has been finalized. Note that the Enceladus-2 flyby will observe the south polar region which has never been imaged before.

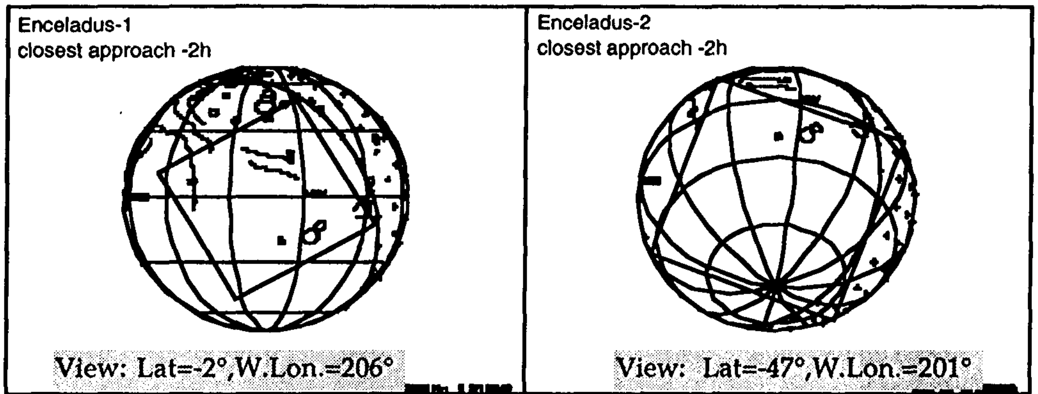


Figure 15 Asymptote Views of First Two Targeted Enceladus Flybys Common to All Tours

For the targeted Iapetus flybys, imaging of the light/dark surface region, which occurs near the boundary of the leading and trailing hemispheres, from an asymptote is considered a must have science observation. Imaging of this region during closest approach is not sufficient since some instruments have long integration times requiring extended observation periods. The Iapetus flyby geometry is identical in the T9-1 and T18-5 tours and provides the desired imaging of this region from an asymptote as shown in Figure 16. In contrast, in the T18-4 Iapetus flyby (Figure 17), the light/dark boundary is in shadow and thus the most of the region can not be observed. This less desirable Iapetus flyby geometry is simply one of the compromises of the T18-4 tour made in order to reduce the satellite encounter frequency and operations stress. Iapetus is the most difficult icy satellite to incorporate due to its large orbital period of ~79 d and its orbital inclination of ~15°.

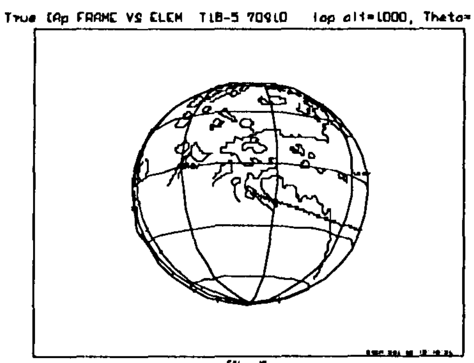


Figure 16 T9-1 and T18-5 Iapetus View

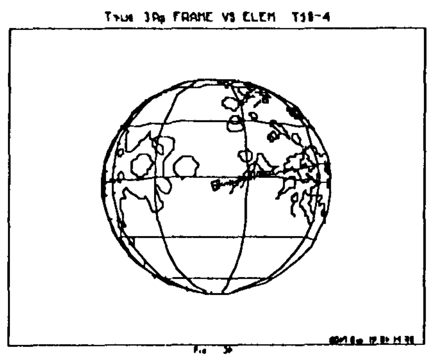


Figure 17 T18-4 Iapetus View

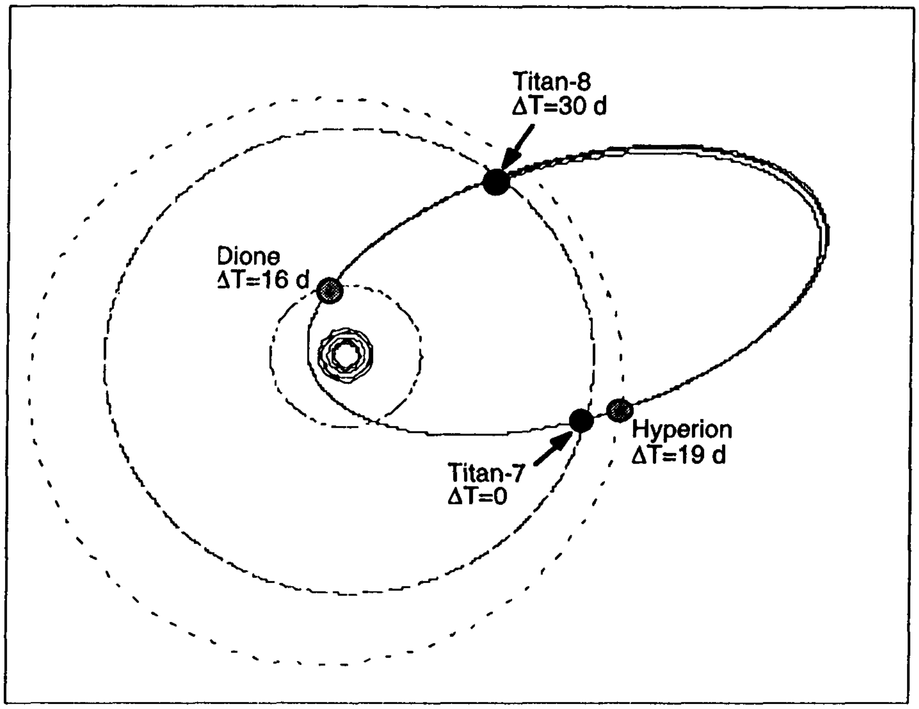


Figure 18 Dione and Hyperion Phasing

All three tours contain ~~an~~ a rare Titan-to-Titan transfer sequence which contains targeted flybys of both Dione and Hyperion as illustrated in Figure 18. Starting at the Titan-7 outbound flyby, the spacecraft completes slightly more than 1 rev before encountering Hyperion ~19 d later. Less than 1 rev and ~16 d later, the spacecraft encounters Dione. The spacecraft then returns to the Titan-8 inbound flyby less than 1 rev and ~16 d later for the next gravity assist. Figure 18 demonstrates that targeted icy satellite flybys must be obtained on orbits which are already targeted to return to Titan, and that all targeted satellite flybys must be spaced at least 16 d apart to meet ground system requirements. Tour T9-1 has a second dual icy satellite flyby sequence in which targeted Tethys and Rhea flybys are obtained between Titan flybys. These two rare phasing opportunities in T9-1 account for the greater number of targeted icy satellite flybys than in either of the two T18 tours.

The tours also contain many nontargeted icy satellite flybys as summarized in Table 6. These distant flybys will be used to supplement the targeted flybys and for some satellites will be the only source of observations. Nontargeted observations are important observations but are not tour design drivers.

Table 6 Nontargeted Icy Satellite Flyby Summary (Distance < 100,000 km)

Tour	Mimas	Enceladus	Tethys	Dione	Rhea	Hyperion	Iapetus
T9-1	5	15	10	5	1	0	0
T18-4	11	11	9	4	0	0	0
T18-5	7	8	5	4	3	0	0

PHASE I

The first phase of the tour is comprised of the initial orbit and Probe delivery previously described and the flybys necessary to achieve 7 Saturn/ring equatorial occultations. Two targeted Enceladus flybys are also obtained. This phase comprises the first 1.2 years of the tour and is the only portion of the tour which has been adopted by the Project since it accomplishes key science requirements and meets all ground system constraints. This portion of the tour will be part of any future tour. A view of the orbits comprising this portion of the tour is shown in Figure 19.

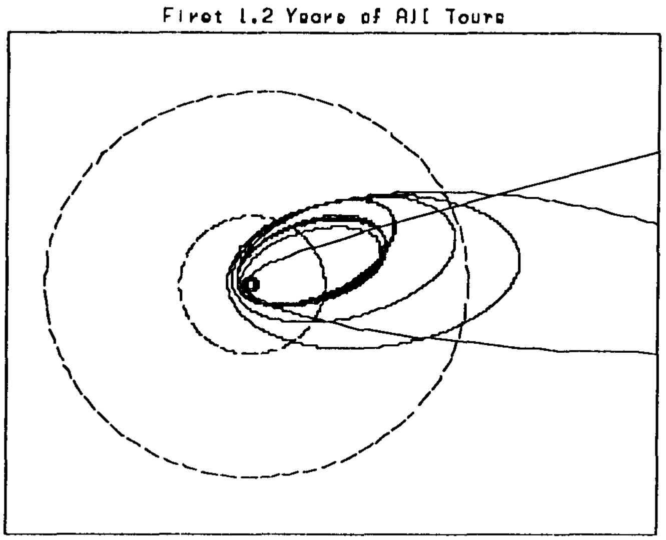


Figure 19 First 1.2 Years of All Tours View From Saturn N. Pole (Direction to Sun Towards Top)

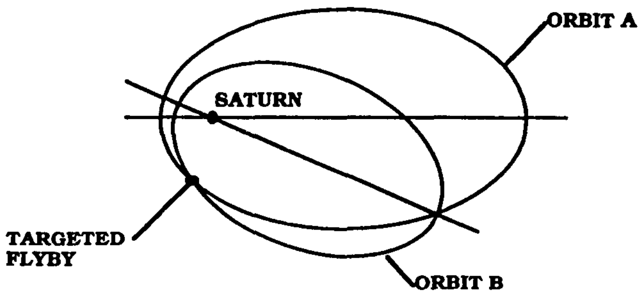
PHASE II AND III

Orbit orientation change may be accomplished by one of two methods: 1) equatorial rotation or 2) 180° transfer. In all three tours, during phase II, orbit apoapsis is rotated clockwise from the dawn to tail orientation, and during phase III, apoapsis is rotated further clockwise from tail to near noon orientation (Table 1, Figure 4). The method by which orbit orientation is changed is the dominant distinguishing feature of these tours. The primary difference between the T9 and T18 tour classes is the method used to change orbit orientation during phase II of the tour, i.e., use of a 180° transfer versus equatorial rotation (Table 1). The primary difference between the T18-4 and T18-5 tours is the orbit periods used in the construction of the 180° transfer sequence. Each method will be briefly discussed with emphasis placed on the 180° transfer sequence since it has not been documented extensively in the literature.

Equatorial Rotation

Equatorial rotation changes orbit orientation in discrete steps of ~15° at each Titan flyby and is characterized by orbits with near zero inclination, i.e., they all lie in Saturn's equatorial plane. Equatorial orbit rotation was successfully used to perform all orbit orientation change in the Galileo tour[2] and this method has been extensively documented[3, 4]. Titan flybys which change orbit period, change the periapsis distance from Saturn which results in a rotation of the line of apsides as shown in Figure 20. The direction in which the line of apsides is rotated depends upon whether the period is increased or decreased and whether the flyby occurs inbound to Saturn periapsis or outbound from Saturn periapsis as illustrated in Figure 20.

To rotate the orbit clockwise, an alternating series of Titan inbound flybys which increase period and outbound flybys which decrease period are used. The most time efficient rotation is obtained by alternating between periods of ~23 d and ~39 d although other orbit periods are occasionally used to achieve additional science objectives such as targeted icy satellites. Both the T18-4 and T18-5 tours use equatorial rotation during the second year of the tour (Table 1). The inclination of all orbits is zero since the plane defined by the inbound position of Titan, Saturn, and the outbound position of Titan lies in the Titan orbital plane which is nearly coincident with Saturn's equatorial plane. The Titan flyby altitude ranges from about ~1850 to ~1950 km during this sequence.



ORBIT ROTATION RULES

Flyby location	Energy (period) increasing flyby	Energy (period) decreasing flyby
Inbound (pre-periapse)	Clockwise	Counterclockwise
Outbound (post-periapse)	Counterclockwise	Clockwise

Figure 20 Equatorial Rotation

180° Transfer

A series of about 15 Titan flybys are required for a full 180° transfer sequence as illustrated in Figure 21 and in the phase III tabular data listed in Tables 3 to 5. A series of constant period orbits increases inclination and decreases orbit eccentricity to a point at which both the ascending and descending nodes of the spacecraft orbit are at Titan's orbital radius (the orbit shown in bold in Figure 21). For example, at Titan-24 in Table 5, both the ascending and descending node distance are ~20 Rs which is the orbital distance of Titan from Saturn. A nonresonant Titan-to-Titan transfer is then performed, i.e., the true anomaly of Titan in its orbit at which it is encountered by the spacecraft on successive flybys is changed by 180° - hence the name a 180° transfer. A series of 16 day period orbits then decreases inclination back to near zero and increases eccentricity back to its original value. Orbit orientation is changed by ~135° in a sun-relative frame over the ~1 year sequence duration. Orbital transfer at high inclination between two different satellites has been discussed previously in the literature[4], but inclined, nonresonant transfers between the same satellite is a tour design technique unique to Cassini tours.

Titan flyby altitudes are generally at the minimum permitted value of 950 km in order to maximize the inclination and eccentricity change at each flyby. Such low altitude Titan flybys are preferred for most science observations. Periapsis may be located above or below the ring plane for duration of the sequence. For these tours, periapsis is placed below the ring plane to obtain desired ring illumination geometry and to permit a couple of intermediate Saturn/ring occultations during the sequence. 180° transfers can also be used to rotate the orbit counter-clockwise by starting the sequence at an outbound Titan flyby. An orbit period of 32 d may be used instead of 16 d, but the maximum inclination of the sequence is reduced to 45° and insufficient time exists to utilize these larger period orbits in the T9 and T18 class tours.

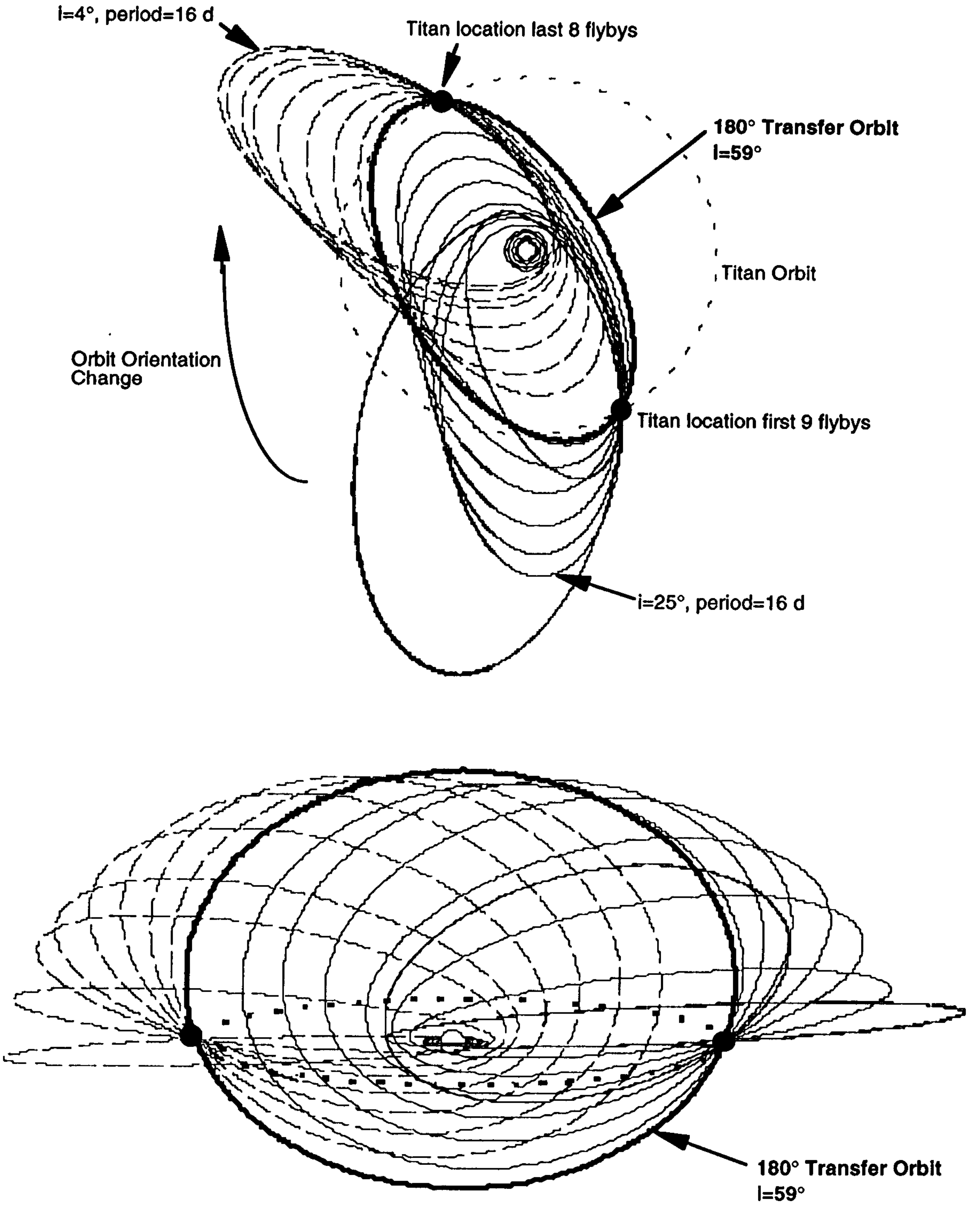


Figure 21 180° Transfer

Comparison of Orbit Orientation Change Methods

Tour T9-1 uses only 180° transfers to change orbit orientation whereas T18-4 and T18-5 use both equatorial rotation and a 180° transfer to change orientation (Table 1). The major advantages and disadvantages of each method are summarized in Table 7 and are subdivided into science and mission operations considerations. Table 7 clearly shows that 180° transfers are more advantageous from the science return standpoint but undesirable from the mission operations standpoint. The T9 class tour is especially stressful to the ground system since two successive 180° transfer sequences are utilized. Mission operations differences between the three tours will be address in detail later in this paper.

Since equatorial rotation is composed of nonresonant Titan-to-Titan transfers, ballistic trajectories are possible and no deterministic ΔV is required. However, 180° transfer sequences are composed mostly of resonant Titan-to-Titan transfers and deterministic ΔV is required to change the Titan-relative aimpoint at each flyby. The close proximity to Saturn (~3 Rs) near the beginning and end of 180° transfer sequences, causes the precession of the spacecraft orbit argument of periapsis due to Saturn oblateness which can only be corrected by expending significant ΔV. For example, a deterministic ΔV of 78 m/s is required to navigate the 180° transfer sequence in phase III of Tour T18-5 which is comprised of 17 Titan flybys.

Table 7 Comparison of Orbit Orientation Change Methods

	Advantages		Disadvantages	
Method	**Science**	**Operations**	**Science**	**Operations**
Equatorial Rotation		• more time between flybys • no deterministic ΔV required	• restricted to zero inclination orbits • higher Titan flyby altitudes	
180° Transfer	• inclined orbits • more Titan flybys • minimum Titan flyby altitude			• less time between flybys • deterministic ΔV much greater

PHASE IV

The final phase of the tour is referred to as the maximum inclination sequence since inclination is raised from near zero to more than 70°. This phase of the tour requires nearly a year and is the only tour phase which has not undergone significant modification during the last decade of Cassini tour design. In order to reach a 70° inclination, the orbit period must be gradually reduced to ~7.1 d at the end of the sequence, but note from the phase IV tabular data in Tables 3 to 5 that the time between flybys is much greater than the required 16 d spacing since two or more revs always occur between Titan flybys. All three tours achieve the required high inclination and low periapsis radius geometry at the end of the sequence. Of the three tours, T18-5 attained the highest inclination at 75.2° which is the highest value achieved by any tour to date.

MISSION OPERATIONS CONSIDERATIONS

Tour ΔV

The ΔV required for each tour is listed in Table 8. During the design stage, tours were required to have margin at the ΔV75 level. After launch, however, the Project raised the confidence level to 95% requiring margin at the ΔV95 level which effectively rules out tour T9-1 and some T18 class tours not documented in this paper from consideration. A total of 503 m/s is available for both deterministic and statistical maneuvers at the 95% confidence level.

Table 8 ΔV Requirements (ΔV in m/s)

	T9-1	T18-4	T18-5
Number of Encounters	60	46	51
Deterministic ΔV	278	239	225
Navigational ΔV75	236	166	188
Navigational ΔV95	337	237	268
ΔV75 Margin (total tour ΔV75= 583 m/s)	69	178	170
ΔV95 Margin (total tour ΔV95= 503 m/s)	-112	27	10

Constraints on Flyby and Maneuver Epochs

All 3 tours meet the annual solar conjunction maneuver and flyby avoidance constraint. All tours also meet the 16 d between flybys spacing constraint with a couple approved exceptions. In both T9-1 and T18-5, the time between Titan and Iapetus is only 10.2 days. Navigation has stated that such a short transfer time might be possible on a case-by-case basis particularly for such an important case as the Iapetus transfer. Also, the time from T18-5's Enceladus-3 encounter to the next Titan encounter is only 13 days. However, since this leg requires no deterministic or statistical maneuvers, navigation has indicated that this flyby should be acceptable. The deterministic maneuver is eliminated by design, and Enceladus' small mass does not mandate a statistical cleanup maneuver.

The ground system has also required that no maneuvers, flybys, or occultations occur during a 9 day period containing the Christmas holiday. Even though one violation of this constraint is permitted, it still has a significant impact on the tour design. To date, only 2 viable tours currently meet this constraint. T18-4 meets the constraint with a single violation, but T18-5 has 3 violations and T9-1 has 2 violations. Simply adding time by inserting extra revs about Saturn in the tours which violate this or other timing related constraints is not possible without 1) sacrificing the targeted icy satellites downstream which are dependent on time critical phasing, and/or 2) failing to complete the tour.

Encounter Frequency

The number of consecutive 16 d intervals is limited to 4 in order to reduce operations stress. After four 16d intervals occur, the ground system requires one interval of 48 d, or 2 intervals of ~32 d, between flybys to act as a break. In principle, any string of consecutive short transfer times will prove stressful to mission operations even if the time between flybys is greater than 16 d.

This "breaks" constraint is met by the T18-4 tour but is violated repeatedly by the T9-1 and T18-5 tours. Figures 22 to 24 plot the time between targeted flybys versus years past the start of the tour. Occurrences of more than 4 successive 16 d intervals are only found in the 180° transfer sequence which occurs during the third year of T18-4 and T18-5, and during both the second and third years of T9-1. Figure 25 shows the average time between flybys for each year in the tour. The average time between flybys is the same for all tours during the first year and similar for all tours during the fourth year. The encounter frequency differs during the middle two years of the tour.

During the second year of the tour, the encounter frequency for T18-4 and T18-5 are quite similar since both are performing equatorial rotation. During this time, however, the T9-1 encounter frequency is quite high since it performs a 180° transfer which is comprised mostly of 16 d orbits. During the third year of all three tours, a 180° transfer sequence is employed, but the number of 16 d intervals is lowest in T18-4 and highest in T9-1. In T18-4, encounter spacing is increased by utilizing larger orbit periods. However, this strategy reduces the number of Titan flybys and thus the number of gravity assists which are available to shape the trajectory since the tours are limited to 4 years. Since less time and flybys are available, less Saturn "real estate" can be covered as illustrated previously by the comparison of T18-4 and T18-5 orbits (Figure 11).

Both T18-4 and T18-5 use a multi-rev sequence to insert a 48 d break once the first few 16 d intervals of the 180° transfer sequence have been completed. This geometry also provides critical ring observations. The T9 Titan-only tour profile left very little time for incorporation of targeted icy satellites, solar conjunction avoidance, and ground systems constraints compliance. Since solar conjunction avoidance is mandatory, either the icy satellite science or some ground system constraints had to be compromised. T9-1 meets the icy satellite requirements but significantly violates the ground system consecutive short orbits constraint. Even though the number of required targeted icy satellites was exceeded in T9-1, it should not be concluded that such flybys are easy to obtain. Unusually advantageous satellite phasing permitted the large number of targeted icy satellite flybys. Adding even a couple breaks of ~48 d to this tour would likely come at the cost of more than half the targeted icy satellite flybys including Iapetus. Due to the high encounter frequency, T9-1 is unlikely to gain ground system approval.

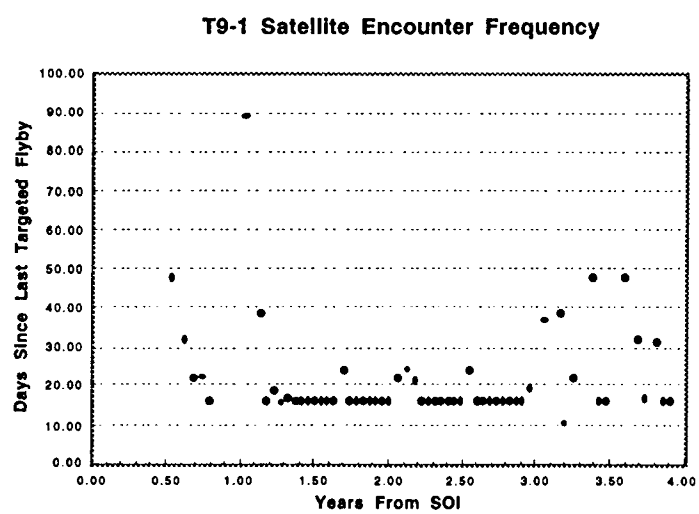


Figure 22 T9-1 Time Between Flybys

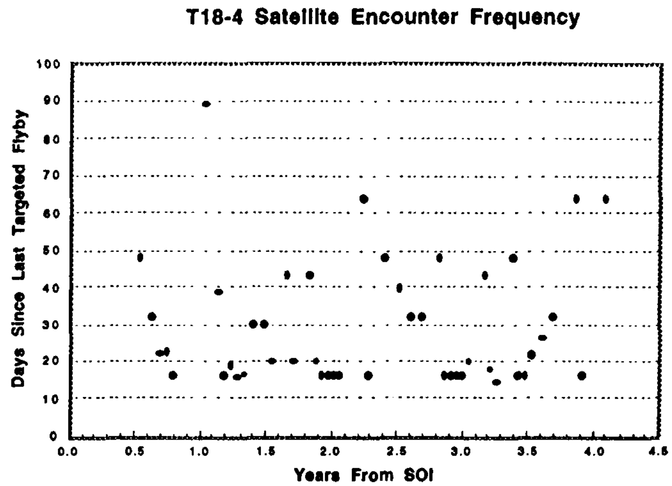


Figure 23 T18-4 Time Between Flybys

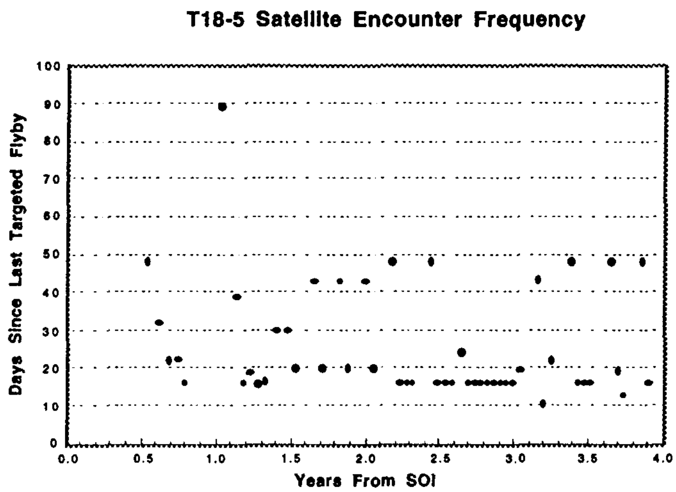


Figure 24 T18-5 Time Between Flybys

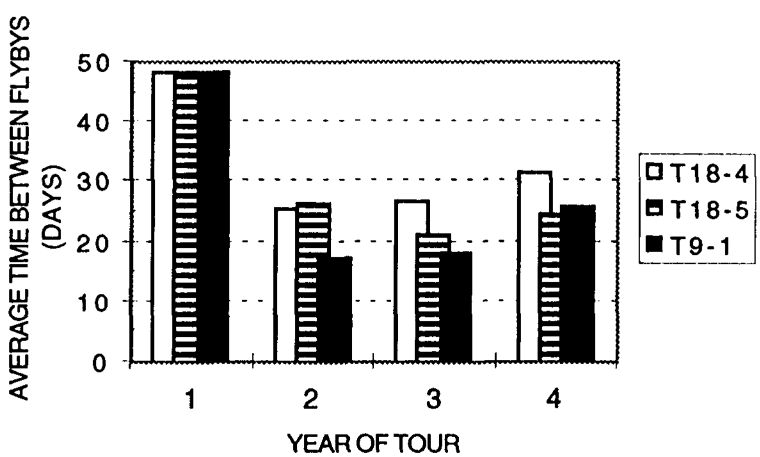


Figure 25 Average Time Between Flybys During Tour

CONCLUSIONS

Any of the three tours described in this paper would make for quite an exciting Cassini mission. The first year of the tour has been finalized, and therefore only the remaining three years are subject to future modification. The tours illustrate the tradeoff between science return and mission operability. The final tour will likely strike a balance between these two often conflicting considerations.

The key discriminator between the three tours is Titan encounter frequency. The T9-1 tour has the most Titan flybys and therefore attains a wider range of science observation geometry's than the other two tours. The T9-1 tour provides the best science return of any tour designed to date, but its high encounter frequency is quite stressful to the ground system. Furthermore, the ΔV required by the T9-1 tour can not meet the 95% confidence level recently levied by the Project which effectively removes this tour from future consideration.

The T18-4 and T18-5 tours illustrate the range of tours available in the T18 tour class. T18-4 meets current ground system requirements by increasing the time between Titan flybys but fails to adequately achieve some "must have" tour geometry's. T18-5 violates encounter frequency constraints to illustrate the potential science gains. The final tour will likely lie somewhere in between these two tours.

ACKNOWLEDGEMENTS

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